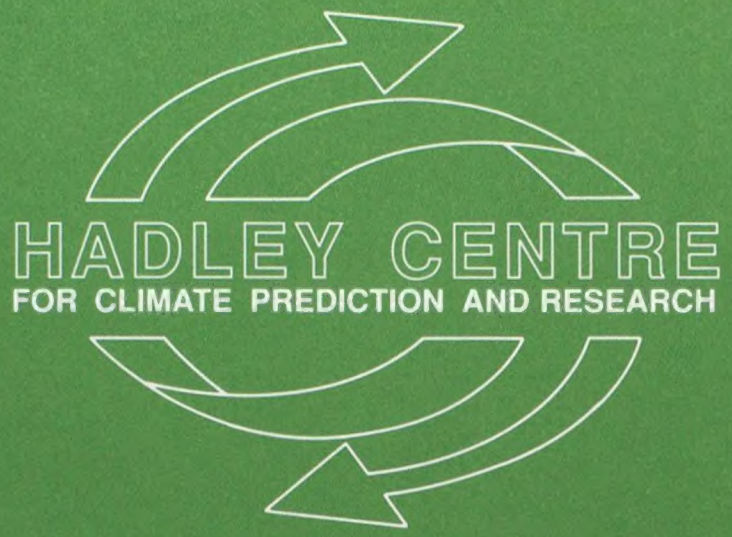

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VALIDATION OF HYDROLOGICAL SCHEMES FOR CLIMATE MODELS AGAINST CATCHMENT DATA

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VALIDATION OF HYDROLOGICAL SCHEMES FOR CLIMATE MODELS AGAINST CATCHMENT DATA

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Abstract

The effects of different hydrological parametrization schemes have been assessed in the framework of a one-dimensional (column) version of such a model by comparing the results with observed data for catchments in southern England. The schemes were the standard one from the UK Meteorological Office model and the Arno or Nanjing model. The Arno scheme is designed to represent the heterogeneity of the hydrological properties over the area, whereas the standard scheme has hydrological characteristics based on data for single points.

The standard scheme gave deficient runoff through most of the year, particularly the summer and autumn. The Arno scheme was found to be capable, with careful choice of model parameters, of simulating the main seasonal variation in runoff for the catchments considered. The principal residual problem was that the soil tended to become too dry in summer. This probably reflects the difficulty of representing a complex hydrological system with one soil moisture variable.

The results also indicated possible improvements in other aspects of the model, including the specification of stomatal resistance and the inclusion of aerosols.

Introduction

The representation of land surface processes, and hydrological processes in particular, is one of the uncertainties of present models used for simulating climate. This was highlighted in the section of the IPCC report on the Scientific Assessment of Climate Change concerned with the validation of the models used in the assessment (Gates et al. (1990)), where there was considerable spread in the simulations of soil moisture between the different models. Improved modelling techniques in this context could substantially improve the ability of such models to predict the effects of perturbations of the environment on climate. This applies not only to the effects of increases in greenhouse gas concentrations, where one of the most important quantities required, rainfall, has been shown to be sensitive to land surface hydrology (e.g. Mintz, 1984). It is also relevant to the simulation of the effects of deforestation on climate where the effects can be sensitive to the details of the representation of the surface hydrological processes (Lean and Rowntree, 1993).

The hydrological parametrization currently in use in the UK

Meteorological Office (MO) model allows for a spatial variability in the precipitation rate over the gridbox in the calculation of surface runoff (Warrilow, 1986a); recently, though not in the scheme as used for this paper, heterogeneity has also been taken account of in calculating the canopy interception (Dolman and Gregory, 1992). However, heterogeneity in the land surface type and its hydrological state are not considered; indeed the soil hydrological characteristics are based on values derived by Clapp and Hornberger (1978) from point-based soil hydrological data. The same is true of other hydrological parametrizations developed for general circulation models in the mid-1980s (Dickinson et al., 1986; Sellers et al., 1986).

In this paper, an attempt is made to validate both the present MO model parametrization and a number of versions of the ARNO or Nanjing model (Todini, personal communication; Wood et al., 1992). The validation of the schemes has been made using a one-dimensional version of the UK Meteorological Office general circulation model (Warrilow, 1986b) which is outlined in the next section. Subsequent sections describe the hydrological parametrizations tested, the catchment data used to test them and the results of the comparisons.

THE MODEL

Advantages of a single column model (SCM)

The hydrology parametrizations are ultimately intended for use in a global model of climate which includes atmospheric dynamics (or advective processes) as well as parametrizations of physical processes. However, there are several advantages, for testing parametrizations of the ground hydrology, in using a one-dimensional or single column model which omits explicit calculation of the dynamics. These advantages include

(i) economy: as well as avoiding the dynamic computations, the calculations need only be made for a single gridpoint rather than on a gridmesh of several thousand points.

(ii) ease of understanding: the complexity of the problem is reduced so facilitating understanding of the mechanisms responsible for the differences between experiments.

(iii) reduction of noise: it is possible to prescribe the forcing applied to the model in an exact form so that the differences are due solely to changes in parametrizations and not to chance variations (or natural variability).

(iv) comparability of different models: again because of the less complex context, results from different models can be more readily compared.

Need for presciption of advective forcing

There are of course disadvantages in the approach. In some

contexts, the most important is the need to specify the advective forcing. This makes the model unsuitable for study of climate change due to large-scale processes (such as the greenhouse effect), since for a given point these processes operate mainly through the advective forcing. If no representation of the advective effects is included, the forcing for a particular point will in general lead to an equilibrium solution different from the real climate at that point. Another problem is that in interpreting the results of experiments with a model of this type, the role of the advective forcing must be taken into account; if the advective forcing is too great, it is possible for a change, which could have a significant effect in a global model, to be nullified by the advective forcing.

Outline of model

The single column model used in the experiments discussed here is a development of that used by Warrilow et al. (1986) (see also Warrilow (1986b)). It was constructed from the Meteorological Office (MO) 11-layer global atmospheric model described by Slingo (1985). The parametrizations of soil hydrology and soil thermal processes were developed by Warrilow et al. (1986) using the single column model, and subsequently incorporated in the global model (see Slingo et al. (1989)).

Model structure

The model consists of the physical parametrizations used in the MO global model. The processes represented are:

(1) Radiative transfer, both solar and longwave, allowing for transmission, absorption and emission by clouds, water vapour, carbon dioxide and ozone.

(2) Surface thermal and hydrological processes; heat transfer in the soil is modelled using a 4-layer model; water has one soil storage layer plus a canopy store which for bare soil represents surface storage; the snow budget is modelled with a one-layer model; provision is made in the global model for combinations of up to 24 land surface types and three soil types, based on the work of Wilson and Henderson-Sellers (1985), though in the single column model only eight vegetation types are considered. These vegetation and soil types determine eight soil-dependent characteristics and eight vegetation-dependent characteristics (for further details see Warrilow (1986a,b), Warrilow and Buckley (1989)).

(3) Boundary layer turbulent transfer processes for heat, moisture and momentum. In the version used in this study, the Clarke (1970) scheme is used, in which the mixing between layers extends up to the third model layer (top at about 2 km), with mixing coefficients reduced in stably stratified conditions.

(4) Convective transfer of heat and moisture, designed to represent an ensemble of buoyant plumes; these may start at

any level if an ascending parcel would be buoyant in the layer above, and continue upwards until the ensemble is calculated to lose buoyancy. The environment is modified according to the compensating descent and the effects of detrainment of heat, moisture and precipitation.

As noted earlier, the effects of advective processes must be represented if a realistic mean climate is to be obtained. This is done by prescribing horizontal advection of air with characteristics (temperature, specific humidity, wind speed) determined according to the seasonally varying climatology of the location. Vertical velocities are similarly prescribed. The characteristics are randomised on the basis of the climatological mean and standard deviation. In any two integrations of the model from a given set of initial data, these randomised characteristics follow an identical course in time, so facilitating comparison of the experiments.

PARAMETRIZATIONS OF LAND SURFACE HYDROLOGY

The Meteorological Office scheme

The Meteorological Office (MO) scheme is described in detail by Warrilow et al. (1986) and by Warrilow (1986a). The scheme represents both surface and subsurface runoff. The surface runoff occurs if the modelled rate of throughfall to the surface exceeds the infiltration capacity of the surface. Allowance is made for the heterogeneity of the precipitation by assuming an exponential frequency distribution of rainfall over the model gridsquare. The runoff is thus

$$Y_S = P \exp(-jF/P)$$

where F is the maximum infiltration rate, P is the precipitation available for infiltration and j represents the fraction of the area over which precipitation falls. The maximum infiltration rates depend on both soil and vegetation types, one of the vegetation-dependent characteristics being an infiltration enhancement factor which is a maximum for forests and a minimum for bare soil. The subsurface runoff process represents drainage of water. For each soil type, values of soil moisture concentration are specified, based on observed soil data, which control the evaporation and drainage. These are:

(1) M_{WT}, the Wilting Point, below which no evaporation is possible; this is the unavailable soil moisture;
(2) M_{CL}, the Critical Point, below which evaporation is limited by soil moisture
(3) M_{SN}, the saturation value, which determines the drainage

Between M_{WT} and M_{CL} the evaporation varies linearly if other factors are unchanged, being equal to the product of a factor

$$\beta = (M-M_{WT})/(M_{CL}-M_{WT}) < 1$$

and a "potential" evaporation E_P calculated allowing for atmospheric and stomatal resistance, but with no allowance for

soil moisture in determining the stomatal resistance, since this is included via the factor β.

The subsurface runoff

$$Y_g = K_S((M-M_{WT})/(M_{SN}-M_{WT}))^c.$$

For the medium soil assumed for the experiments reported here, the exponent c is 8, K_S , the saturated hydraulic conductivity, is 6.5 mm/h and $M_{WT}=0.105$, $M_{CL}=0.17$ and $M_{SN}=0.46$.

We must also specify a vegetation type which determines the root depth and so the actual soil moisture capacity etc. We assumed long grass to be the vegetation type for southern England, for which the root depth is taken to be 1 metre; thus the quantity of available soil moisture needed for evaporation not to be limited is (0.17-0.105) m = 6.5 cm. Other characteristics for long grass assumed in the model are:

snowfree albedo=0.2; deep snow albedo=0.6;
stomatal resistance=60 s/m; roughness length=6 cm;
canopy capacity=1.8 mm; vegetation fraction=0.85;
vegetation infiltration enhancement factor=2.

<u>The ARNO hydrological parametrization</u>

The ARNO scheme (Todini, personal communication), also known as the Nanjing model (Wood et al., 1992), is a parametrization of the surface hydrology which relates to evaporation, soil moisture storage and runoff. However, in most of the tests reported here the evaporation scheme was not used, the standard formulation being retained, so focussing attention on the dependence of model behaviour on the runoff parametrization. Like the MO scheme, the runoff is separated into a surface runoff (Y_S) directly dependent on the precipitation (P) reaching the ground from rainfall, throughfall and snowmelt, and a drainage term (Y_g) which depends only on soil moisture.

It is assumed, as in Wood et al. (1992), that infiltration capacities vary within a catchment or model gridbox due to variations in elevation, slope, and soil and vegetation types. The infiltration capacity (i) is assumed to vary between zero and a maximum value (i_m) according to a cumulative frequency distribution function:

$$i = i_m [1-(1-A)^{1/B}] \qquad (1)$$

where A is the fraction of the area with infiltration capacity less than i; B is a parameter which characterises the shape of the cumulative frequency distribution and can be chosen to optimise the model's fit to the observations. The soil moisture content W stored in the area when points with infiltration capacity up to some value i_o less than i_m are saturated (and so will generate runoff if rain occurs) can be shown by integration to be:

$$W = [i_m/(1+B)] [1-(1-A_S)^{(1/B)}] \qquad (2)$$

where A_S is the value of A corresponding to i_o. The total infiltration capacity W_M (W_C in Wood et al) is thus:

$$W_M = i_m / (1+B). \qquad (3)$$

The runoff from the saturated part of the area can be shown to be:

$$Y_S=P-(W_M-W)+W_M[(1-W/W_M)^{(1/(1+B))}-P/(W_M(1+B))]^{1+B} \qquad (4)$$

If the term in square brackets is negative, it is assumed to be zero. The identity of this to the form used by Wood et al. (1992) follows from the equality of $(1-i_o/i_m)$ and $(1-W/W_M)^{(1/(1+B))}$ deducible from (1), (2) and (3) above.

For the catchments in the Arno basin studied by Todini (personal communication), B varies from 0.01 to 0.5 as heterogeneity increases. Note that, unlike the MO scheme, the parametrization allows surface runoff to be dependent on the soil moisture. However, in the form used in these tests, it does not allow for the heterogeneity of the precipitation

It is useful to note that equation (4) can be approximated for small B by

$$Y_S = P\ B\ W / (W_M-W) \qquad (5)$$

i.e. surface runoff is approximately proportional to precipitation, B and $W/(W_M-W)$.

The drainage used in the scheme is as proposed by Todini:

$$Y_g = D_1\ (W/W_M) + (D_{max}-D_1)[(W-W_{DR})/(W_M-W_{DR})]^{DX} \qquad (6)$$

It thus varies linearly up to a critical value W_{DR} which is assumed to be 0.7 W_M in Todini's scheme, and then exponentially above this value. The range of variation of DX was from 1 to 2.2 in Todini's studies (personal communication) (Table 1), while for most catchments he used values of the drainage parameters such that $(D_{max}-D_1) >> D_1$; with DX equal to 1, drainage thus increases very rapidly above $W=W_{DR}$, so that W is effectively limited to W_{DR}. In a heterogeneous catchment such a sharp cutoff to soil moisture seems unlikely, so for the Thames catchment DX was assumed to be 2.2 and adjustments to the drainage were obtained by varying D_1 and D_{max} (Table 1). Wood et al. (1992) assume a linear dependence of drainage or base flow on soil moisture so assuming the second term on the right of (6) to be zero.

Analysis of hydrological data for the Thames catchment

The SCM may be used for any location. Warrilow et al. (1986) studied the sensitivity of the model to its parameter specifications for southern England. Warrilow et al.'s analysis indicated that the model could give a reasonable simulation of the climate for that area so it was natural to

choose a river basin in that location for assessments of the hydrology parametrization. From the point of view of developing a parametrization for use in a model with mesh size 100km or more, it was desirable to choose a relatively large river basin. One of the longest records of runoff available is that dating from 1883 for the Thames at Teddington and more recently at nearby Kingston, the data for which measure runoff from a basin with an area of about 10000 km^2. For recent years the data are available not only as gauged but also in "naturalised" form to allow for extractions for the public water supply. These naturalised data were supplied by the Institute of Hydrology (Wallingford) (IH) and have been used for purposes of comparison with the SCM computations. Some data, including the 1883-1980 means were obtained from Institute of Hydrology (1985). It was confirmed by comparison with data for other catchments given in this publication that the relation of runoff to precipitation in the Thames basin was typical of other large catchments in relatively low-lying parts of Britain.

Table 2 shows data for two periods, the full record to 1980, and the recent record since the introduction of new measuring techniques at Kingston in 1975. There is an increase in runoff of about 10% in the recent period, which may be a measurement problem, or could be due to the transfer of rainfall from summer, when most rainfall is evaporated, to spring. The seasonal patterns for the two periods are as similar as might be expected given the differences in precipitation (P); there is a winter peak in both Y and Y/P, and a late summer minimum. The similarity of the levels of P during the winter peak and summer low flows point clearly to the dominance of evaporation in determining the seasonal variation, although the greater rainfall of the preceding months no doubt makes some contribution (72 mm/month for September-December compared with 52 for April -June).

There is considerable interannual variability in the Thames record, as shown by an analysis of the runoff and rainfall (meaning always here precipitation, i.e. rainfall plus snowfall) for the year starting in September. (This choice for the runoff year seems likely to minimise the effect on the analysis of changes in ground water content, though it cannot eliminate them.) Figure 1 compares rainfall and runoff for the period 1968/69 to 1988/89 for which data were first supplied from IH. There appears to be a good linear relation. Moreover, the departures from the approximate fit shown can be explained with some confidence. For example, the years below the line (less yield than expected for given precipitation) are 1973, 1985 and 1977; each of these followed a dry year - 1972, 1984, 1976 are ranked respectively 4th, 6th and 1st in dryness. Of the other 3 years in the 6 driest, 1970, 1973 and 1989, the first two were also followed by years below the expected runoff (the rainfall data for 1990 were not complete in the data from IH at the time of the analysis). From the Thames record, one may estimate the runoff for a given rainfall; this will be useful in section 5 when we assess the

model simulations. Approximately the linear relation is

$$Y = 0.52P - 114 \text{ (mm/year)}. \qquad (7)$$

Over a year, the ground water budget may be written

$$d(SM) = P-Y-E \qquad (8)$$

where d(SM) is the change in storage over the year and E is evaporation. Substituting (7) in (8):

$$E + d(SM) = 114 + 0.48P \qquad (9)$$

This equation should not be regarded as havig general validity for the catchment; for example, in the longterm, zero precipitation must, in the absence of irrigation, lead to zero evaporation and runoff. Nonetheless, it does provide some insight into the relation between evaporation and precipitation over the Thames basin. If the storage change term is ignored, one would conclude that evaporation in the region is considerably limited by precipitation, though caution would be advisable, as commonly in considering such relations, because of the possibility that both apparently related variables might be influenced by a third. However, in this case the obvious relation due to cloud actually acts in the opposite direction - i.e. increased rainfall is likely to be associated with more cloud which decreases the energy available for evaporation.

It is likely that the soil moisture storage term (d(SM)) decreases (increases) in dry (wet) years; however it is beyond the scope of this study to quantify this, so it cannot be established to what extent evaporation is limited by soil moisture deficits in dry years. A multiple regression analysis of the Thames record coupled with use of evaporation estimation methods such as that used in the MORECS (Thompson et al. (1981)) should be informative .

RESULTS OF TESTING OF HYDROLOGICAL SCHEMES

Experiments

The tests of the hydrological schemes were made by integrating the single column model for periods of from one to four years. Table 3 lists the experiments discussed here. The integrations were all started from January 16, to allow comparison with the results of Warrilow et al. (1986).

Broad features of the simulation

Although many of the comparisons were limited to one or two years, a useful perspective is provided by considering first a four-year run of the control experiment (Expt. C). The major features of the seasonal variation in the model were shown by Warrilow et al (1986b) and are not repeated in detail here. However, it is instructive to look at the seasonal variation of the main water balance components for two contrasting

years, Years 2 and 3 of Expt. C (Table 4). (see next subsection for runoff data)

Broadly speaking, available soil moisture, after reaching a peak in late winter of slightly above the field capacity (defined by Warrilow et al (1986) as that soil moisture content at which the drainage reaches 0.03 mm/hour - about 15 cm for medium soil), decreases through spring and summer as evaporation increases with solar radiation input. The model in the form tested here tends to dry out in summer, with soil moisture often limiting evaporation. In some years this drying is so severe that evaporation virtually ceases during dry spells, as in Year 3 in Table 4, though in Year 2 there is little restriction because of the heavy summer rains in that year. The problem of excessive drying is explored further later in this section.

Table 5 shows that the model exhibits considerable interannual variability, and emphasises the relative wetness of Year 2. The variation in precipitation P is particularly notable; the sample is too small for a proper comparison with observed data but variations of this magnitude are certainly found in the observed data; for example, for the Thames basin, the rainfalls for the wettest and driest years in the 1883-1980 period were 1001 mm (1903) and 414 mm (1921) respectively. Note that in the wet Year 2, the summer drying of the soil was much less than in the other years, particularly Years 3 and 4, when minimum SM was 0.05 cm or less. Most of the comparisons later in this Section are restricted to the first two years. While this is partly for reasons of computational economy, it is also justified by the greater similarity of the ODM rainfall in these years (average 678 mm/year) to the observed Thames basin rainfall (717 mm/year). The results for runoff are discussed in the next section.

Rainfall and runoff with different hydrological schemes

The runoff in the control experiment shown in Table 5 is much smaller than observed for the Thames basin. The average runoff for the four years is only 81 mm, whereas in the Thames basin the expected runoff with a rainfall of 608 mm is 200 mm. This implies an evaporation of 408 mm, compared with the model's 507 mm. Evidently, the model is failing to apportion the precipitation correctly between evaporation and runoff. An analysis of the model's seasonal variation of rainfall and runoff is made in Table 6.

The comparison with the Thames basin data shows that, though the likeness to reality increases with increasing B (or heterogeneity) with the ARNO scheme, the result, even for B=0.5, still leaves much scope for improvement. Evidently, the runoff needs to be increased and the evaporation diminished. In the following subsections, we consider the effects on the results of modifying the formulations of the drainage, the radiation which in part determines the evaporation, and the evaporation itself.

Effects of modification of drainage parameters in ARNO scheme

The runoff is too small in summer in all versions discussed so far. It is even too small compared with a dry year such as 1976 when monthly runoff in summer for the Thames catchment fell to 3 mm.

One possibility which should be considered is whether a constant base flow is evident. A constant flow is allowed for in the ARNO scheme though Todini sets it to zero in all his runs. If there were one, then in a dry year one might expect runoff to be a larger fraction of rainfall. This is not apparent - for example in 1976, with low rainfall from April to August, fractions are

54, 19, 19, 15 ,11 compared with the 1883-1980 mean of
46, 33, 23, 15, 14.

However, this could be due to evaporation being a larger fraction of rainfall in dry months.

The weak summer runoff can be alleviated to some extent in the ARNO scheme by increasing the drainage term. Todini has used values for D_1, the drainage coefficient up to the onset of rapid drainage, of as high as 0.15 mm/h. This is 108 mm/mth and would probably give too dry a soil. However, there is good evidence from the Thames data that drainage is an important component. For example, in April, when E of about 40 mm is to be expected, so that with P of 40 mm, little runoff is expected directly from the rainfall, the runoff was at least 15 mm except in two years with very dry conditions (1973, 1976). If we assume that this rate can occur with SM of about 12 cm, then a D_1 of about 0.03 mm/h appears reasonable.

It is appropriate at this point to emphasise that in this study we are attempting the task of modelling a highly complex system with just one hydrological quantity, near-surface water content. Complete success would be remarkable, as it would imply that much of that complex structure had no effect on the runoff. In particular, we are ignoring the ground water aquifers which are recognised to be an important component of the Thames basin flow.

Expt. BD was run to test the effect of increased drainage. Compared with the experiments with less drainage over most of the soil moisture range, the runoff is greater, as expected. Over two years, the runoff averages 159 mm/year, and the seasonal distribution (not shown) is much improved. On the other hand the minimum summer soil moisture is reduced due to the increased runoff. A more detailed assessment of a run with drainage included is given later in this section.

Effects of modification of the model radiation

The net radiation obtained in the model averaged 65 W/m^2 over the four years of the control experiment. This is well in excess of that observed for Hamburg (about 51 W/m^2) (Kasten, 1977), although as Hamburg is at slightly higher latitude (53.5N compared with about 51.7N for the Thames basin), the

Thames value should be slightly higher. Further comparisons with observed data may be made for solar radiation, with particular emphasis on the maximum daily amounts observed; these ought to be similar or, because the sampling period is shorter, less in the model. Data were studied for June in Year 1; the largest downward solar radiation values were 403 W/m^2 on two cloudless days, 25 and 26 June, with four other days exceeding 380 W/m^2. The mean June downward solar flux was about 240 W/m^2 (for quite a wet month). This may be compared with data for stations in the south of England (Meteorological Office 1980). For Kew (51 28 N, 00 19 W) (1951-75), monthly mean June values range from 163.1 in 1956 to 256.3 W/m^2 in 1975. The Easthampstead (51 23 N, 00 47 W) values are similar with a 1965-75 mean of about 216 W/m^2. The maximum values in the model of 403 W/m^2 may be compared with observed maxima. For Kew for 1966-75, this was 340 in June, though the May maximum was 361.9. The Easthampstead maximum was 358 (in June). These suggest that the model values of 403 W/m^2 are excessive.

A possible reason for this is the model's neglect of the radiative effects of aerosol. Estimates of these (Unsworth and Monteith 1972) suggest that, for much of the British Isles, as much as 15% of the extraterrestrial downward solar flux is absorbed or back-scattered by aerosol in the lowest 3km on cloudless days. In June, this is about 70 W/m^2 for clear days and the annual mean effect could be of order 20 W/m^2. Tanre et al (1984) obtained estimates of depletion of the solar beam by 30 W/m^2 over central Europe in July in the ECMWF model due to aerosol (10-30 over UK)

An approximate representation of the absorption due to aerosol was coded into the radiation scheme. The scattering and reflection due to aerosol were not represented. The absorption was confined to the lowest three layers of the model. The aerosol absorptions in these layers for zero zenith angle were 2% in the lowest layer (about 200 m thick), 4% in the next 600 m and 2% in the upper layer which is about 1.1 km thick. These figures reflect the expected decrease with height (see Unsworth and Monteith 1972 for discussion). The actual absorptions are greater than this because of the nonzero zenith angle. A difficulty arises for large zenith angles for which a very large fraction of the solar beam can be absorbed with this approach. Estimates of the seasonal variation of the optical depth due to aerosol suggest that aerosol amounts are less in winter than summer (Unsworth and Monteith 1972). The problems of representing the seasonal variation and allowing for large zenith angles were avoided in the model by placing a lower limit of 0.5 on cos z (the cosine of the zenith angle). For diffuse radiation cos z was assumed to be 0.6 consistently with the treatment of the diffuse beam in other contexts.

Experiments were carried out with this representation of aerosols included, both with the MO hydrology (Expt. CA) and with the ARNO scheme in the form used in Expt. BD (Expt. BA).

The effects of the aerosols on solar radiation were sufficient to reduce the average downward solar radiation in the model on June 26 (with clear skies as in the control) to 357 W/m^2, close to the extreme observed values discussed earlier. Arguably, a larger reduction than this could be justified in the mean, but these experiments will suffice to indicate the sensitivity of the results to the inclusion of aerosol.

Table 7 shows the effects on the two year mean values. Considering first the Expt. CA with the MO parametrization, the RN column shows that the objective of reducing the available energy has been achieved. The decreases are nearly 8 W/m^2 averaged over the year. However the partitioning of the available energy has also changed so that the reduction in latent heat flux is less than that in sensible heat flux. This can be explained by two mechanisms. One is that discussed in the next subsection by which a negative feedback limits the separation between experiments using different evaporation formulations. The other is due to the heating of the atmosphere by aerosol absorption of radiation; the higher boundary layer temperatures lead to a reduction in the sensible heat fluxes so that the fraction of the available energy used for evaporation is increased. This is evident in the greater reduction in H than in LE from C to CA.

The differences between BA and BD are similar to those of CA from C. However, the decrease in evaporation is smaller, and that in sensible flux greater because of the more arid summer in BD than C.

Effects of modifications of the model evaporation

A possible contributor to the summer aridity in the model is excessive evaporation (E). One possible way of decreasing evaporation is to increase the stomatal resistance; Warrilow et al (1986) suggest that a 30 s/m change in stomatal resistance will change E by 5%, or about 25 mm/year (0.07 mm/day). It is difficult to specify the stomatal resistance for a region such as the Thames basin with any confidence. The data proposed on the basis of literature surveys and experience by Thompson et al. (1981) suggest that the value used in the experiments discussed so far, 60 s/m, is probably too low: their values for bare soil (100), conifers (70 at minimum, over 100 for typical daytime temperatures and humidities), deciduous trees (80 at minimum (full leaf)) and uplands (100-120), are all above 60. Only riparian (near river-bank) grassland in April and May, and cereals and some other crops in active growth are given lower values than 60 s/m. An experiment (BA90) was therefore run with stomatal resistance increased from 60 to 90 s/m.

The results are summarized in Table 8. The increase in stomatal resistance reduces the evaporation as expected, though not by as much as the 25 mm/year obtained by Warrilow et al (1986). This may be because of the summer drying in our experiments which was less marked in theirs. The result is about one third the size of that obtained with an increase to

150 s/m (Expt. BD15 compared with BD), confirming the linearity with r_s found by Warrilow et al. (1986). The reduced evaporation increases the soil moisture and so also the runoff. Precipitation is hardly affected. The largest differences in soil moisture are nearly 1 cm in late spring; those in summer are less because of the negative feedback which arises as drying of the soil reduces evaporation, and winter values differ little because of the negative feedback caused by saturation of the soil.

The seasonal variation of the runoff and precipitation are documented in Table 9. The ratio of one to the other is broadly similar to the observed for the Thames basin for the 1883-1980 period. The main fault is that the summer runoff is still deficient by up to 50%.

A comparison has also been made with data for eastern England, specifically the catchments of the Deben (at Naunton Hall), Stour (Langham), Colne (Lexden), Chelmer (Springfield) and Blackwater (Appleford Bridge) taken as one group and then averaged with equal weighting, to allow for relative catchment sizes, with data for the Nene at Orton and Witham at Claypole Mill (all data from Institute of Hydrology (1985)). The observed annual average precipitation for these catchments of about 600 mm is closer to the model's. The ratio of runoff to rainfall is in good agreement both for the annual means and through much of the year. A longer run of the model would be needed to confirm whether results as good as these can be obtained consistently.

The results are clearly a considerable improvement on those obtained with the MO scheme, or with the ARNO scheme without drainage, as illustrated for Year 1 in Fig 2. Note that the summer runoff/precipitation ratios are improved in Year 2 (not in Fig 2) when the rainfall is greater.

Although the runoff results obtained in Expt. BA90 are clearly more realistic than those from Expt. C, the enhancement of the drainage term which is responsible for much of the improvement has exacerbated the summer aridity problem. The solution to this is beyond the present study; however, it may be useful to note that, as discussed in Institute of Hydrology (1986), a substantial contribution to runoff comes from groundwater; as discussed earlier, one cannot expect to model this and the soil moisture in the root zone with a single variable. Further progress towards a solution would probably require that this be taken into account as is already done with more sophisticated models.

6. Conclusions

The conclusions of this paper may be summarised as follows.
(1) The ARNO hydrological parametrization assessed in this study with the Meteorological Office one-dimensional model is capable, with careful choice of model parameters, of

simulating the major seasonal runoff characteristics of the Thames basin. The parameters chosen differed from those first suggested but were within the range of values previously used. One remaining problem was that the soil becomes too dry in summer; this reflects the difficulty of representing a complex system with a single hydrological variable.

(2) The existing MO hydrology parametrization scheme gave results which were unsatisfactory, with deficient runoff in summer. This is attributed to the use of hydrological models based on point data and the consequent omission of the effect of heterogeneities on the hydrological characteristics.

(3) The tests also provided evidence concerning other aspects of the model parametrizations. Modifications of those for evaporation and radiative transfer were assessed. The results were sensitive to the specification of stomatal resistance, with increased values contributing to a more realistic simulation. The omission of atmospheric absorption of solar radiation by aerosol in the boundary layer was also found to exacerbate drying in summer.

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TABLES

Table 1 Values of parameters in the ARNO scheme

	B	W_M (mm)	D_1 (mm/h)	D_{max} (mm/h)	DX
Maximum (Todini)	0.5	250	0.15	8.0	2.2
Minimum (Todini)	0.01	80	0.001	0.1	1.0
Initial value tried	0.01	200	0.001	6.0	2.2
Final value used	0.5	200	0.03	0.5	2.2

Table 2 Thames basin runoff (Y) and rainfall (P) data (multi-year means) and Y/P as a percentage
(Unit for Y and P: mm averaged for the basin)

	J	F	M	A	M	J	J	A	S	O	N	D	Y
1883-1980													
P	65	50	51	48	53	52	59	65	57	72	73	72	717
Y	37	33	31	22	17	12	9	9	9	13	22	30	245
Y/P	57	66	61	46	32	23	15	14	16	18	30	42	34
1975-1989													
P	67	44	72	45	60	52	45	57	58	73	60	79	712
Y	38	33	36	28	22	16	11	10	9	15	18	31	267
Y/P	56	75	49	61	36	30	23	18	16	20	31	39	37

Table 3 List of experiments

Acronym	Scheme	r_S (s/m)	B	D_1 (mm/h)	D_{max}	
C	MO	60				
B.01	ARNO	60	0.01	.001	6	
B0.1	ARNO	60	0.1	.001	6	
B0.5	ARNO	60	0.5	.001	6	
BD	ARNO	60	0.5	.03	0.5	
CA	MO	60				Aerosol
BA	ARNO	60	0.5	.03	0.5	Aerosol
BA90	ARNO	90	0.5	.03	0.5	Aerosol
BAAb	ARNO	60	0.5	.03	0.5	Aerosol; ARNO β for Evap.
Beta-	ARNO	60	0.5	.001	6	Quadratic β for Evap.
C150	MO	150				
B150	ARNO	150	0.5	.001	6	
BD15	ARNO	150	0.5	.03	0.5	

Table 4 Monthly water balance components for Experiment C

	J	F	M	A	M	J	J	A	S	O	N	D	Y
Precipitation (mm)													
Yr2	46	43	100	41	47	44	117	65	68	50	36	39	696
Yr3	87	52	73	24	19	25	67	18	27	30	39	29	494
Evaporation (mm)													
Yr2	7	16	36	68	98	107	95	78	51	28	10	5	599
Yr3	8	14	35	69	97	70	47	39	13	13	8	4	417
Soil moisture (cm)													
Yr2	13	16	18	16	12	6	4	4	4	6	9	10	10
Yr3	18	19	19	15	9	2	1	1	0.5	2	3	7	8

Table 5 Annual data from 4-year run of control experiment
(first two columns are Year and Experiment Name)

		T*	SMC	P	Y	E	RN	H	LE	SMmin	Tmax
1	C	9.46	8.58	612	32	543	62.5	19.7	42.9	0.44(D242)	23.6
2	C	8.89	10.3	744	87	595	64.9	17.9	47.0	2.17(D169)	21.6
3	C	9.66	7.88	453	105	421	68.4	35.0	33.2	0.02(D182)	28.6
4	C	9.94	9.17	623	98	471	67.5	30.3	37.2	0.05(D252)	27.3
Mean		9.49	8.98	608	81	507	65.8	25.7	40.1		

Units: T* (surface temperature):^{o}C; SM (soil moisture): cm;
P (precipitation), E (evaporation), Y (runoff): mm/year;
RN (surface net radiation), H (sensible heat flux), LE (latent heat flux): W/m^2;
SMmin (annual minimum SM) and Tmax (mean T* of warmest day) as for SM and T* respectively (dates given as Dnnn where June 1 is D137, July 1 is D167, August 1 is D198 etc).

Table 6 Modelled seasonal variation of precipitation (P) and runoff (Y) (mm/month) for standard parametrization and for ARNO scheme with different B (Year 1) and comparison with observed for Thames catchment (OBS)

	J[2]	F	M	A	M	J	J	A	S	O	N	D	Y
Precipitation (P)[1]													
B.01	38	75	46	56	57	59	72	37	32	43	28	63	602
Runoff (Y)													
C	0.9	3.2	18	6.6	2.5	0.7	0.2	0.0	0	0.0	0	0.1	32
B.01	0.6	21	29	1.0	0.7	0.5	0.2	0.1	0.1	0.2	0.2	0.6	55
B0.1	2.9	21	30	3.6	2.8	1.9	0.6	0.1	0.1	0.6	0.6	3.1	67
B0.5	7.6	22	30	11	7.1	4.7	1.7	0.2	0.4	1.6	1.7	8.8	95
Y/P%													
B0.5	17	29	66	19	13	8	2	1	1	4	6	14	15
OBS	57	66	61	46	32	23	15	14	16	18	30	42	34

Notes 1: Only B.01 given as P varies little with experiment
2: The Year 1 January data are for the last 16 days of the first January and the first 15 days of the second.

Table 7 Effects on annually averaged and extreme results of including aerosol absorption

Year	Exp	T*	SMC	P	Y	E	RN	H	LE	SMmin	
		°C	cm	(mm/year)			(W / m^2)			(Yr 1)	(Yr 2)
1+2	C	9.17	9.4	678	59	569	63.7	18.8	44.9	0.44	2.17
1+2	CA	8.80	9.87	653	73	528	56.3	14.6	41.7	0.55	2.07
1+2	BD	9.75	6.18	653	159	469	64.5	27.4	37.0	0.13	0.13
1+2	BA	9.26	6.55	634	169	437	55.2	20.7	34.5	0.17	0.23

Table 8 Average effects of evaporation changes (Years 1-2)

Year	Exp	T*	SMC	P	Y	E	RN	H	LE	SMmin (Y1,Y2)
		°C	cm	(mm/year)			(W / m^2)			cm
1+2	BA	9.26	6.55	634	169	437	55.2	20.7	34.5	0.17	0.23
1+2	BA90	9.32	6.94	633	179	425	54.8	21.3	33.5	0.34	0.58

Table 9 Runoff and precipitation with enhanced drainage, aerosols and increased stomatal resistance (Expt. BA90)

	J	F	M	A	M	J	J	A	S	O	N	D	Y
RUNOFF (mm)													
Y1	*7	29	28	22	14	9.1	4.3	1.4	1.4	4.5	6.0	16	155
Y2	22	22	51	23	10	3.4	6.7	6.6	8.6	10	11	15	204
Y3	*26												
AVE	27	26	40	22	12	6.3	5.5	4.0	5.0	7.3	8.6	15	179
PRECIP (mm)													
Y1	*14	71	44	52	50	54	63	33	30	42	27	62	566
Y2	45	42	99	36	39	32	110	58	67	48	34	40	696
Y3	*69												
AVE	64	56	72	44	45	43	87	45	49	45	30	51	632
RUNOFF/PRECIP (%)													
BA90	43	46	55	50	28	15	6	9	10	16	29	30	28.3
OBS[1]	57	66	61	46	32	23	15	14	16	18	30	42	34
OBS[2]	49	63	54	37	24	13	11	9	10	15	23	35	28

Notes 1: Data for Thames catchment.
2: Data for eastern England catchments as described in text.

Appendix 1

Table of results from various experiments

Year	Exp	T* °C	SMC cm	P	Y	E	RN	H	LE	SMmin cm	Tmax °C
				(mm/year)			(W / m^2)				
1	C	9.46	8.58	612	32	543	62.5	19.7	42.9	0.44/D241	23.6
1	B.01	9.66	7.31	604	55	509	62.7	22.5	40.2	0.24/D235	25.7
1	B0.1	9.75	7.07	601	67	498	63.1	23.7	39.4	0.20/D235	26.0
1	B0.5	9.88	6.57	595	95	475	63.3	25.8	37.5	0.16/D235	26.4
1	Beta	9.83	6.69	597	97	475	62.3	24.8	37.5	0.18/D235	26.2
1	C150	9.69	10.7	602	43	498	62.3	23.0	39.3	2.98/D245	22.8
1	B150									1.06/D241	24.4
1	BD15	10.2	6.65	583	158	412	62.6	30.1	32.5	0.65/D241	25.8
2	C	8.89	10.3	744	87	595	64.9	17.9	47.0		
2	BD15	9.66	7.79	710	209	453	65.3	29.5	35.7		
										(Yr 2)	
1+2	C	9.17	9.4	678	59	569	63.7	18.8	44.9	2.17/D169	21.6
1+2	CA	8.80	9.87	653	73	528	56.3	14.6	41.7	2.07/D169	21.4
1+2	BD	9.75	6.18	653	159	469	64.5	27.4	37.0	0.13/D169	24.2
1+2	BA	9.26	6.55	634	169	437	55.2	20.7	34.5	0.23/D169	24.7
1+2	BA90	9.32	6.94	633	179	425	54.8	21.3	33.5	0.58/D169	23.4
1+2	BAAb	9.45	7.57	627	194	401	54.4	22.7	31.7	1.38/D169	24.3
1+2	C150	9.50	11.9	661	96	507	63.4	23.4	40.1	5.11/D169	22.3
1+2	B150	9.78	8.4	653	156	463	64.0	27.4	36.6	1.79/D169	23.9
1+2	BD15	9.92	7.22	647	184	433	63.9	29.8	34.1	1.15/D169	24.7
										(Yr 3)	
3+4	C	9.80	8.53	538	101	446	67.9	32.7	35.2	0.02/D182	28.6
3+4	C150	9.96	9.64	529	124	421	67.4	34.2	33.3	0.42/D241	26.7
3+4	B150	10.2	7.22	524	149	370	67.8	38.5	29.2	0.12/D182	28.5
3	C	9.66	7.88	453	105	421	68.4	35.0	33.2	0.02/D182	28.6
										(Yr 4)	
4	C	9.94	9.17	623	98	471	67.5	30.3	37.2	0.05/D252	27.3
4	C150									0.58/D250	24.3
4	B150									0.37/D250	26.5

Appendix 2

Additional results on effects of modifications in evaporation

Because of the form of the dependence of evaporation on soil moisture (Fig. A1), this could be ameliorated in the middle range of SM values by assuming that there is a spread of SM about the mean value. A "top hat" frequency distribution was considered for the model: soil moisture over the area was assumed to be distributed evenly between two values M_{min} and M_{max} where, if M differed from both M_{WT} and M_{SN} by more than $0.5S_{max}$, with S_{max} a function of the heterogeneity parameter,

$$M_{min} = M - 0.5S_{max}; \quad M_{max} = M + 0.5S_{max}$$

Otherwise, the spread of M was assumed to be symmetric about M and bounded by whichever of M_{WT} and M_{SN} was closer to M. Fig A1 shows the variation of the beta parameter for the standard formulation ($S_{max} = 0$) and for two nonzero values of S_{max}. It was realised that the variation could be approximated by a quadratic (see Fig A1) which would avoid the discontinuous behaviour near $M = M_{WT} + 0.5S_{max}$ and this form was used in one run (Beta-) with the Arno scheme. However, the effects were small and the change was not used in subsequent runs. The effect on soil moisture approached 1 cm at Days 150-160, and runoff was increased slightly (about 2% over the year). The effect on evaporation was small partly for the usual reason: if evaporation for a given soil moisture is reduced this increases soil moisture so largely compensating for the changed formulation. Moreover as there was no difference in the β value for small values of SM (<3.25 cm for medium soil), convergence between the solutions occurred in the dry summer conditions.

The ARNO scheme for parametrization of evaporation (Todini, p.c.) similarly involves use of a β parameter:

$$\beta = 1-A_U + A_U(W/W_M)$$

where the unsaturated fraction

$$A_U = (1-W/W_M)^B$$

This is a function of the moisture content W, with β equal to 1 for $W = W_M$. For small heterogeneity B, the variation with W is very close to linear. As the area becomes increasingly heterogeneous, it is assumed that an increasing fraction remains saturated so that area mean evaporation is higher for a given average soil moisture; however, even with large heterogeneity (B=0.5), the evaporation (Fig A1) is well below that with the MO scheme. Whilst this would certainly reduce the evaporation and so increase runoff, it is difficult to justify the assumption that even a small decrease of soil moisture below saturation limits evaporation below that obtained with the appropriate stomatal resistance. In the absence of heterogeneity (B=0), the parametrization should approach that for a single site for which studies such as that

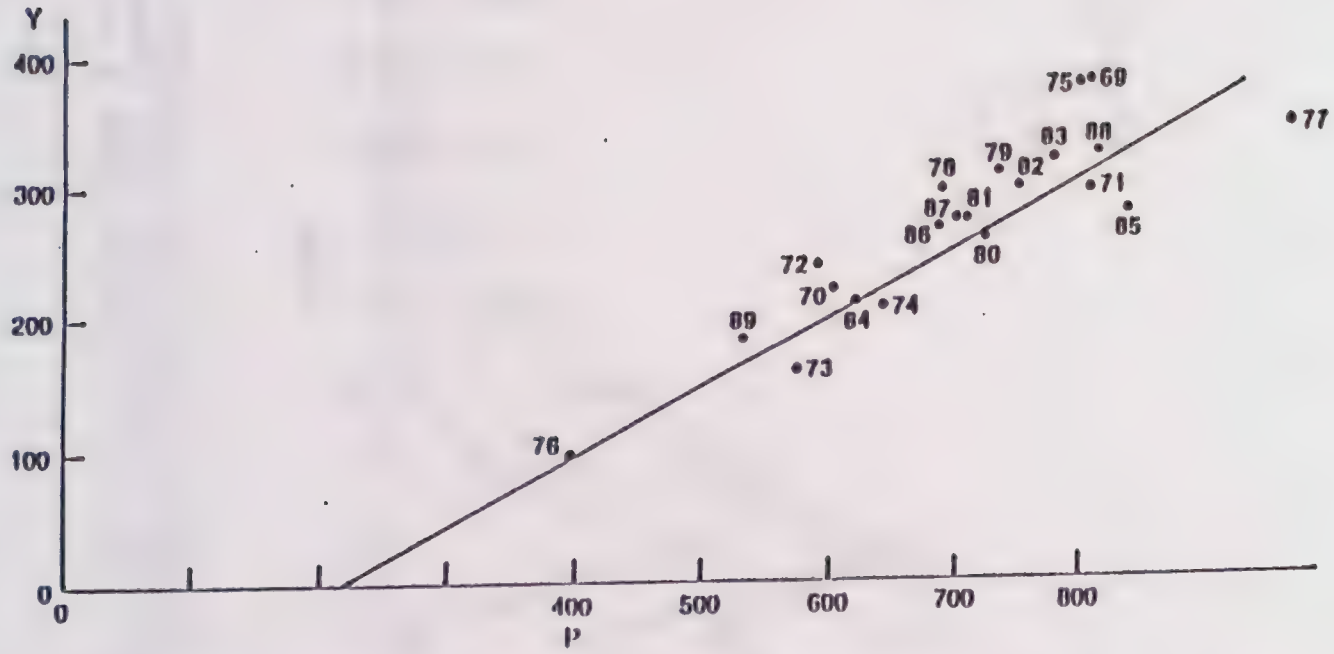

Figure 1 Annual runoff (Y) and precipitation (P) for the Thames basin above Kingston for September to August for 1968/69 to 1988/89 (Unit: mm).

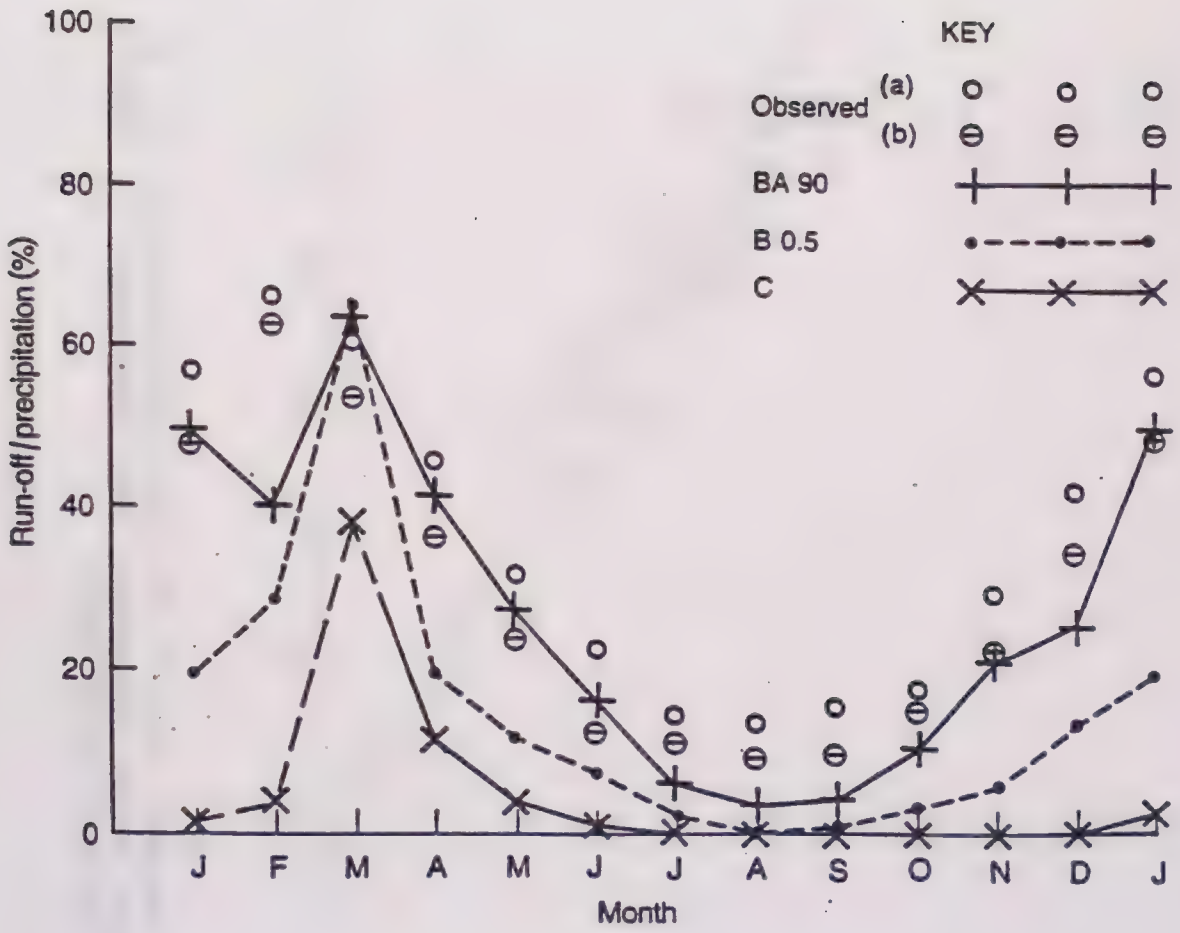

Figure 2 The seasonal variation of runoff as a percentage of precipitation for observed data ((a) Thames, 1883-1980; (b) East Anglia - see text), and for Year 1 of three runs of the model.

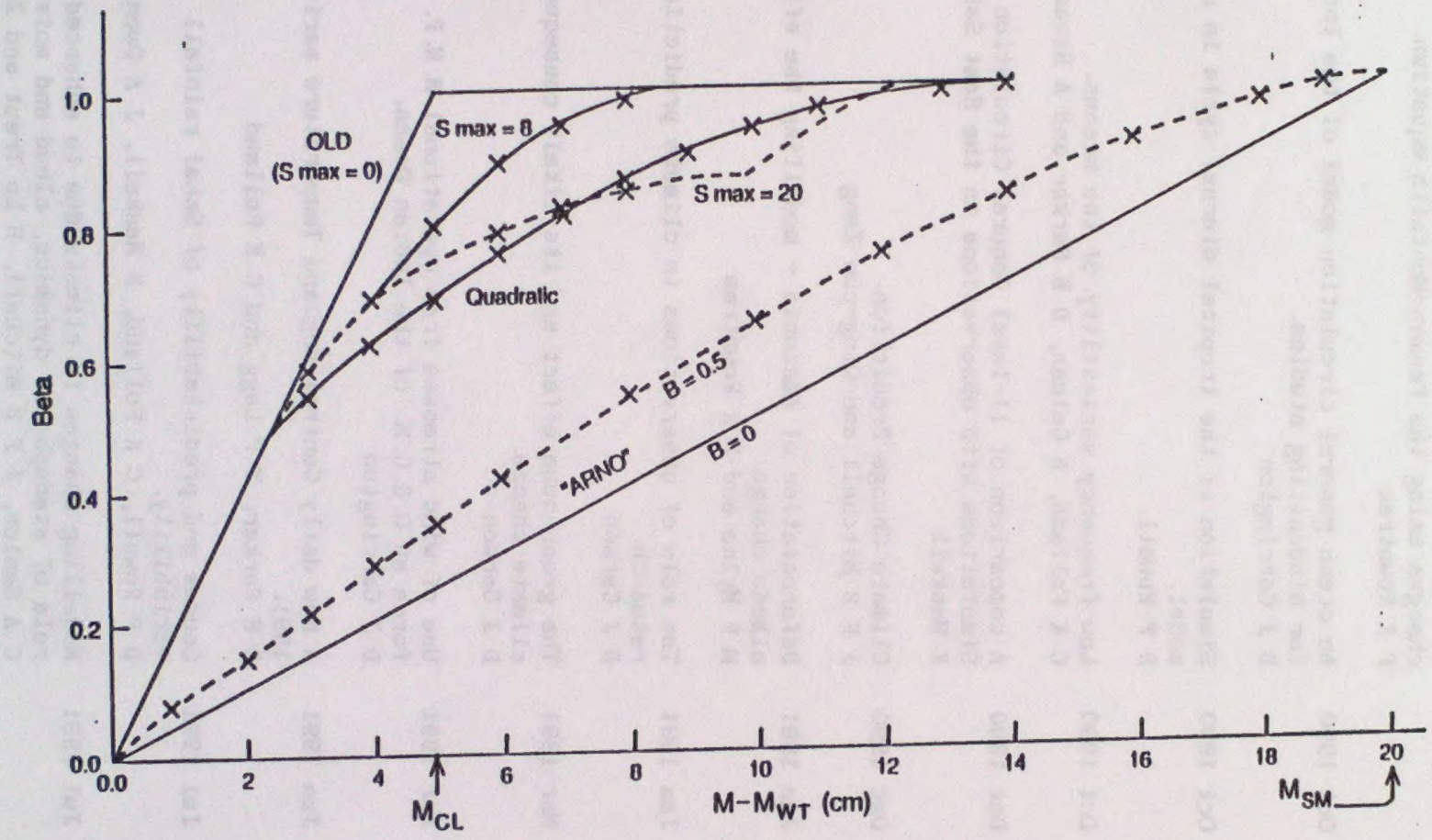

Figure A1 Dependence of the parameter (β) relating actual evaporation to the evaporation when not limited by soil moisture, for different schemes.

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